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Published in:
Proceedings of the 13th workshop on Cool Stars, Stellar Systems, and the Sun.

Publication date:
2005

Document Version
Publisher's PDF, also known as Version of record

ACCRETION CHANNELING IN CLASSICAL T TAURI STARS

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Abstract

It is now accepted that accretion in classical T Tauri stars is controlled by the stellar magnetosphere, as opposed to the traditional disk boundary layer model. The magnetosphere truncates the disk at several stellar radii allowing material to couple to the field and fall toward the star. Observations indicate the presence of hot spots on the stellar surface where accretion flows impact the photosphere. By considering magnetic fields with a realistic degree of complexity we demonstrate that the geometry of the field strongly affects the location and distribution of hot spots - the signatures of accretion.

Key words: Stars: pre-main sequence – Stars: magnetic fields – Stars: formation – Stars: coronae

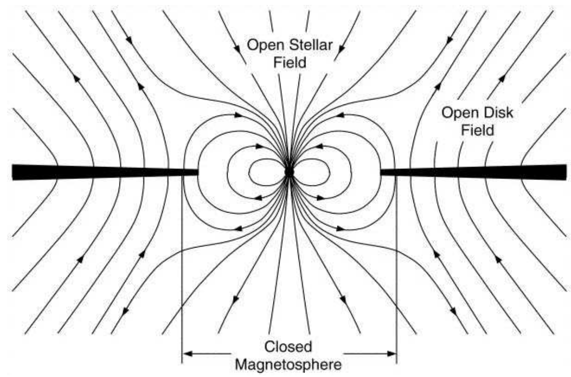

Figure 1. An idealised model of the magnetic field structure of a CTTS. There are three main classes of field line: (i). closed field lines near to the stellar surface which contain the corona, (ii). closed field lines that thread the circumstellar disk which can channel in-falling material onto the star and (iii). regions of open field which can carry outflows. Figure reproduced, with permission, from Goodson et al. (1997).

1. Introduction

Classical T Tauri stars (CTTS) are young low mass protostars still contracting along Hayashi tracks toward the main sequence. They are surrounded by a dusty disk of material that is slowly spiralling in toward the central star. At some radial distance from the star the magnetic pressure from the stellar magnetosphere begins to exceed the ram pressure of the disk material, and the disk is truncated. Material is loaded onto field lines and channelled onto the star, producing hot spots where the funnelled matter streams impact the stellar photosphere. Figure 1 illustrates the magnetic field structure that we believe CTTS may have. Close to the star there are closed field lines that contain the high temperature but low density corona, whilst further out there are closed field lines which thread the lower temperature but higher density circumstellar disk. It is along this latter set of field lines that accretion may proceed. There are also regions of open field which carry outflows in the form of a wind, and in some cases, as large collimated bipolar jets.

Photometric observations of CTTS reveal excess continuum emission in both the IR and UV wavebands that is superimposed on the stellar photospheric spectrum. This effect was first noticed by Joy (1945) when observing T Tau, which became the prototype for a new class of star. This additional continuum emission reduces the equivalent width of absorption lines (see e.g. Kenyon & Hartmann 1987; Bertout et al. 1988; Stempels & Piskunov 2003) and is observed to vary with time. The shape and intensity of emission lines show irregular variations on both long and short timescales, indicating that CTTS are highly dynamical systems.

High reddening indicates the presence of dusty circumstellar disks. The UV excess is believed to originate from the accretion shock region, where in-falling material in magnetically channelled accretion flows impact the stellar surface. The material shocks and radiates away its kinetic energy producing excess emission in the UV. Photometric monitoring reveals hot spots on the stellar surface (Bouvier et al. 1988) which are associated with the accretion shocks and are commonly observed (Bouvier et al. 1993).

Spectroscopic observations of CTTS reveal many strong emission lines, whilst inverse P-Cygni profiles are commonly observed (e.g. Edwards et al. 1994). The widths of the redshifted absorption components of such profiles indicate that material impacts the star at several hundred kms^{-1}. Emission line measurements give typical mass accretion rates of 10^{-9}–10^{-7} $\mathrm{M}_{\odot}\mathrm{yr}^{-1}$. An overview of the observational characteristics of T Tauri stars can be found in the review by Bertout (1989).

In §2 we discuss current magnetospheric accretion models and highlight the observational techniques that have been used to detect magnetic fields in CTTS. In §3 we introduce the first steps in modelling the accretion process with realistic magnetic fields, and briefly outline future work to study how the X-ray emission may be affected by the presence of a disk and by active accretion. Our conclusions are in §4.

2. Magnetospheric accretion models

Magnetospheric accretion models were originally developed to model accretion onto magnetised neutron stars (Ghosh & Lamb 1979), and later adapted to CTTS systems by Camenzind (1990) and Königl (1991). In these models the disk is truncated at some distance above the photosphere, where material couples to the magnetic field forming accretion columns. It is assumed that the field is closed and is dipolar on the largest scale. For typical mass accretion rates the disk is disrupted at a distance of a few stellar radii (Basri & Bertout 1989; Hartigan et al. 1995; Collier Cameron & Campbell 1993; Gullbring et al. 1998). These models provide a magnetic coupling between the star and regions of the disk that rotate slowly, thus avoiding the effect of spinning up the star. Magnetospheric models also predict the existence of accretion columns where the accreting material is channelled onto the star, producing localised hot spots upon impact. They also provide a natural theoretical basis for a connection between the accretion and ejection processes, such as disk winds and collimated jets (e.g. Ferreira 1997).

One of most comprehensive attempts to model the accretion process is the Shu model (Shu et al. 1994, and subsequent papers). In the Ghosh and Lamb model the field lines thread the disk at a range of radii, which will constantly distort and stretch the field, leading to a complicated reconnection event (Aly & Kuijpers 1990; van Ballegooijen 1994). The Shu model avoids this problem by assuming that the magnetic field lines thread the disk at, or very close to, the corotation radius, so that the field rotates as a solid body. For the field lines that penetrate interior to corotation the disk material will flow onto the star, whilst those field lines that penetrate exterior to corotation will carry material away in the form of a disk wind. The Shu model thus provides a mechanism for accretion with the simultaneous slowing of the stellar rotation rate.

However, recent observational results indicate that the accretion process is highly time dependent. Time dependent modelling will require a combination of long term monitoring of CTTS systems combined with magnetohydrodynamic (MHD) simulations. Some observations appear to show evidence for reconnection events which indicate a constantly changing magnetic field structure (Alencar et al. 2001; Ardila et al. 2002). Bouvier et al. (2003) present observations of AA Tau which indicate cyclic eclipses of the star by an inner disk warp, that appears to have dispersed for one rotation period, only to return. During this missing eclipse both the line fluxes and veiling were strongly reduced and the variability was less, indicating that not only has the inner disk warp vanished, but at the same time the accretion process appears to have switched off. The numerical simulations of Romanova et al. (2003) suggest the creation of both a standard disk warp and another warping effect created by the tendency of accreting gas to corotate with the stellar magnetosphere. Their simulations also indicate that magnetic field lines undergoing differential rotation are quickly distorted after only a few stellar rotation periods.

Differential rotation between field line footpoints may lead to expansion of the field, followed by a reconnection event (Aly & Kuijpers 1990; Goodson et al. 1997; Goodson & Winglee 1999). These models successfully manage to combine time dependent accretion and outflow episodes, with material being ejected from the system by the opening of the field (Hayashi et al. 1996; Romanova et al. 2002). Simulations carried out by Romanova et al. (2003) have illustrated that the accretion process is rather more complicated than was first imagined, even though their work is restricted to a dipolar field.

The encouraging result from the MHD modelling that has been undertaken so far is that in almost all models there is a connection between the accretion and ejection processes. Goodson et al. (1997) show that dipole field lines threading the disk can also drive disk winds and jets, whilst in addition Hirose et al. (1997) argue that reconnection events may also explain the slow rotation rates of CTTS.

The majority of models of the accretion process in CTTS have taken realistic physics, but are limited to simple dipolar magnetic fields. There is mounting observational evidence to suggest that CTTS have non-dipolar field geometries. Johns-Krull & Gafford (2002) demonstrate that different CTTS have similar average surface field strengths, and therefore observational differences between systems can be attributed to differences in the field geometry.

2.1. Magnetic field detection

Magnetospheric accretion models assume that the field is strong enough to disrupt the disk at a distance of a few stellar radii. This requires a surface field strength of at least 1 kG. Such strong magnetic fields have been detected in a number of different systems using a variety of methods. Average surface fields of typically 2-3 kG have been measured most successfully from Zeeman broadened spectral lines (Johns-Krull et al. 1999b). Other methods have yielded similar results from measurements of the circular polarization of lines which are sensitive to the presence of a magnetic field (Johns-Krull et al. 1999a), from the equivalent width enhancement of optically thick lines (Basri et al. 1992; Guenther et al. 1999) and from electroncyclotron maser emission - a coherent emission process from mildly relativistic electrons trapped inside flux tubes close to the stellar surface (Smith et al. 2003). However, current models of CTTS assume the same atmospheric structure for both the magnetic and non-magnetic regions of the photosphere, which may lead to inaccuracies in the measured field strengths (Safier 1999). This problem may be resolved by estimating the Zeeman broadening in near-IR lines, which have been shown to insensitive to the assumed model atmosphere (Valenti et al. 1995). An accessible overview of the various observational techniques is given by Johns-Krull et al. (2003).

Although these methods have been used to put constraints on the magnetic field geometry of CTTS (see Valenti, this proceedings), the question of what is the actual magnetic field topology remains open. However, without prior knowledge of the field geometry it is possible to investigate how different field structures would affect the accretion process.

3. Realistic magnetic fields

From Zeeman-Doppler images it is possible to extrapolate stellar magnetic fields by assuming that the field is potential. At the moment we do not have the necessary observations of CTTS, but we do have for the K-type dwarf stars LQ Hya and AB Dor (Donati & Collier Cameron 1997; Donati 1999), which have very different field topologies (Jardine et al. 2002a; Hussain et al. 2002; McIvor et al. 2003; McIvor et al. 2004). Using their field structures as an example we can adjust the stellar parameters (mass, radius and rotation period) to construct a simple model of a CTTS, surrounded by a thin accretion disk, with an opening angle of approximately 10°.

The method for extrapolating the field follows that employed by Jardine et al. (2002a). Assuming the magnetic field $\mathbf{B}$ is potential, or current-free, then $\nabla \times \mathbf{B} = 0$. This condition is satisfied by writing the field in terms of a scalar flux function Ψ, such that $\mathbf{B} = -\nabla\Psi$. Thus in order to ensure that the field is divergence-free ($\nabla.\mathbf{B} = 0$), Ψ must satisfy Laplace's equation, $\nabla^2\Psi = 0$; the solution of which is a linear combination of spherical harmonics,

$$\Psi = \sum_{l=1}^{N} \sum_{m=-l}^{l} \left[a_{lm} r^l + b_{lm} r^{-(l+1)} \right] P_{lm}(\theta) e^{im\phi},$$

where P_{lm} denote the associated Legendre functions. It then follows that the magnetic field components at any point (r, θ, ϕ) are,

$$\begin{aligned} B_r &= -\sum_{l=1}^{N} \sum_{m=-l}^{l} \left[l a_{lm} r^{l-1} - (l+1) b_{lm} r^{-(l+2)} \right] \times \\ &\quad P_{lm}(\theta) e^{im\phi} \\ B_\theta &= -\sum_{l=1}^{N} \sum_{m=-l}^{l} \left[a_{lm} r^{l-1} + b_{lm} r^{-(l+2)} \right] \frac{d}{d\theta} P_{lm}(\theta) e^{im\phi} \\ B_\phi &= -\sum_{l=1}^{N} \sum_{m=-l}^{l} \left[a_{lm} r^{l-1} + b_{lm} r^{-(l+2)} \right] \frac{P_{lm}(\theta)}{\sin\theta} i m e^{im\phi}. \end{aligned}$$

The coefficients a_{lm} and b_{lm} are determined from the radial field at the stellar surface obtained from Zeeman-Doppler maps and also by assuming that at some height R_s above the surface the field becomes radial and hence $B_\theta(R_s) = 0$ (Altschuler & Newkirk 1969). In order to calculate the field we used a modified version of a code originally developed by van Ballegooijen et al. (1998).

3.1. Accreting field extrapolations

The initial field extrapolation yields regions of open and closed field, which may be separated into field lines that thread the circumstellar disk and those which do not. This latter set comprises of both open and closed field. However, as the magnetic pressure drops with height above the stellar surface, some of the closed field may not be able to contain the coronal plasma. For a specified coronal base pressure some field lines, which otherwise would have been closed, are distorted and eventually blown open. For an isothermal corona it is possible to calculate the gas pressure at each point along a closed field line. Assuming that the plasma along the field is in hydrostatic equilibrium then,

$$p = p_0 \exp\left(\frac{1}{c_s^2} \oint_s g_s ds \right), \tag{1}$$

where c_s is the isothermal sound speed and g_s the component of the effective gravity along the field line such that, $g_s = \mathbf{g}.\mathbf{B}/|\mathbf{B}|$. The effective gravity in spherical coordinates for a star with rotation rate ω is,

$$\mathbf{g}(r, \theta, \phi) = \left(-\frac{GM_*}{r^2} + \omega^2 r \sin^2\theta, \omega^2 r \sin\theta \cos\theta, 0 \right). \tag{2}$$

We can then calculate how the plasma β, the ratio of gas to magnetic pressure, changes along each field line. If at any point along a field line $\beta > 1$, then we assume that the field line is blown open. This effect is incorporated into our model by setting the coronal (gas) pressure to zero whenever it exceeds the magnetic pressure ($\beta > 1$). This same condition is also applied to the set of field lines which thread the disk.

Of the field lines that thread the disk we have determined the first set that have the potential to carry an

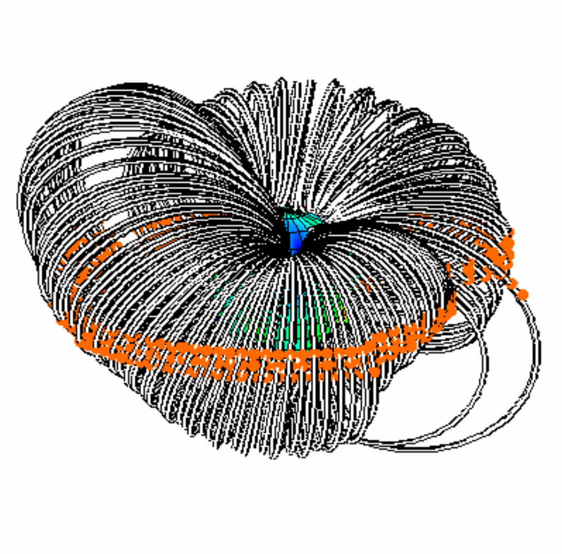

Figure 2. The first set of accreting field lines for a model CTTS with a field topology that resembles that of LQ Hya, viewed from a longitude of 280° and latitude of 20°. Points indicate where the field lines would thread the accretion disk. Only accreting field lines are shown, which resemble a tilted and warped dipole.

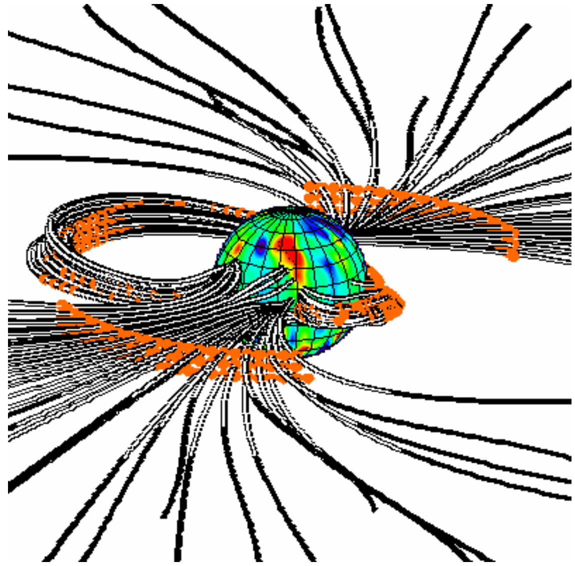

Figure 3. As Figure 2 but for a CTTS with a field topology similar to that of AB Dor. Much of the accretion appears to proceed along open field. In one hemisphere much of the closed field has been blown open by the coronal pressure exceeding the magnetic pressure.

accretion flow. We have assumed that accretion may proceed along closed field line loops provided that the effective gravity where the field threads the disk points toward the star. Along open field lines accretion will occur from the corotation radius. Even if a closed field line satisfies this accretion condition, it may be unable to contain the isothermal corona, and would be blown open. We have set the coronal pressure to zero for such field lines, and have assumed that as material spirals in through the disk, at any particular azimuthal angle, it will accrete along the first possible field line that is able to both support accretion, and also contain the coronal plasma. Field lines at the same azimuth interior to any accreting field lines are assumed to be shielded and do not see any of the flow. This assumption will be relaxed in future work. We also assume that the field is static and is therefore not distorted by the disk.

Figures 2 and 3 show the first set of accreting field lines obtained by surrounding the field extrapolations of LQ Hya and AB Dor with an accretion disk, creating a model of a CTTS with a mass of $M_*=0.27\ M_\odot$, radius, $R_*=3.37\ R_\odot$, and rotation period, $P_{rot}=8.5$ days. This matches the observational data from Gullbring et al. (1998) for the CTTS DF Tau. The results in the two cases are very different. For the LQ Hya-like field the set of accreting field lines resembles a dipole field that has been tilted and warped. For the AB Dor-like field most of the accretion appears to proceed along the open field, with accretion along closed field lines mainly occurring in one hemisphere. The closed field in the other hemisphere has mostly been blown open by the coronal pressure. This may indicate that the disk extends a lot closer to the stellar surface, or more likely for the AB Dor-like field structure, that the closed field is opened but still able to accrete by threading the disk interior to corotation. However, Safier (1998) criticises current magnetospheric accretion models for not including the effects of a stellar corona. He argues that the inclusion of a realistic corona blows open most of the closed field with the eventual net effect being that the disk would extend closer to the star, with accretion taking place from well within the corotation radius. This would of course imply that we do not yet understand why CTTS are slower rotators than their older relations weak line T Tauri stars (WTTS).

Different magnetic field geometries have a large effect on the detectable signatures of accretion. The location of the accreting field line footpoints are shown in Figures 4 and 5. These give an indication of how different field geometries control the shape, location and distribution of hot spots. In the case of the LQ Hya-like field the accretion footpoints span a range of latitudes with the formation of a distorted accretion ring around the northern pole. The AB Dor-like field yields very different results, with the accretion footpoints producing a series of discrete hot spots about the star's equator. Observational evidence already

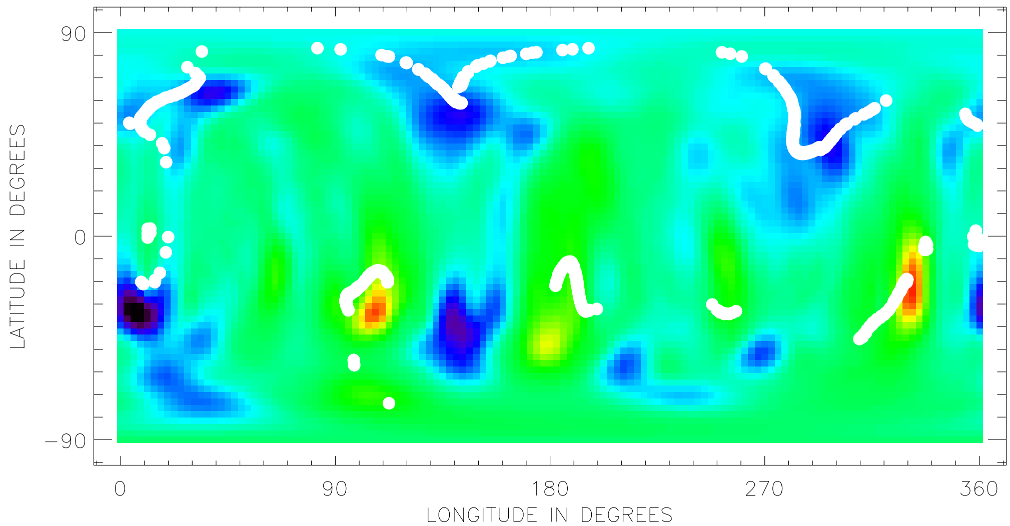

Figure 4. *Surface magnetogram used in Figure 2. Blue represents regions of negative field, and red regions of positive field. The footpoints of the accreting field lines are indicated by white circles. For this field topology the hot spots in the northern hemisphere are mainly located at mid to high latitudes (with the formation of a distorted accretion ring around the pole), and at low to mid latitudes in the southern hemisphere.*

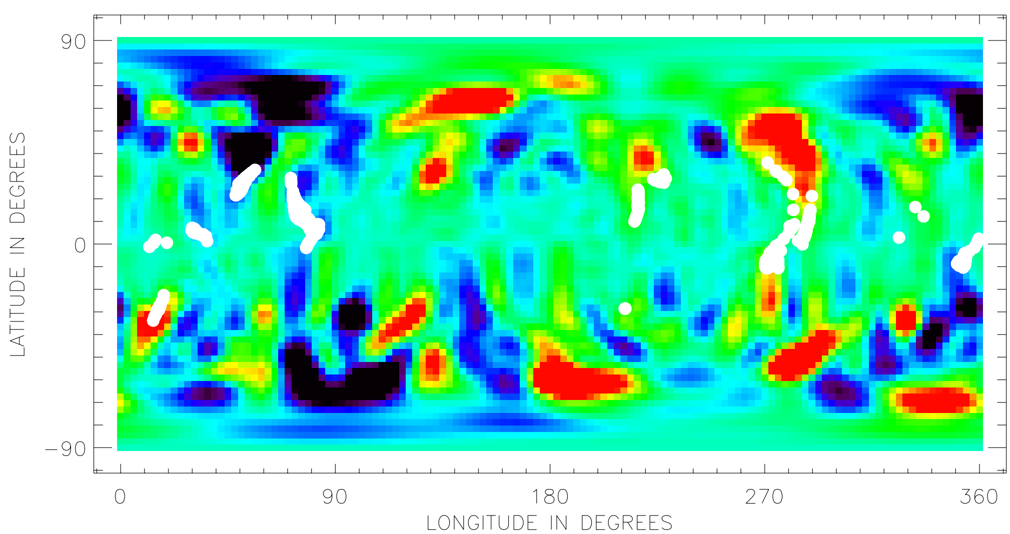

Figure 5. *As Figure 4 but with the surface magnetogram used in Figure 3. For this field topology the accreting field line footpoints indicate the formation of discrete hot spots unevenly distributed about the star's equator, from low to mid latitudes.*

exists which indicates the presence of hot spots at a range of different latitudes (see Valenti, this proceedings). In future work we shall obtain the filling factors of accretion for our CTTS models, which may then be compared to observations.

3.2. Future work: X-ray emission

In future we shall be able to investigate how the presence of a disk and of active accretion, affects the coronal X-ray emission. The method of modelling the X-ray emission follows that in Jardine et al. (2002b). Firstly we determine the pressure structure of our isothermal corona assuming it is in hydrostatic equilibrium. This is obtained from equation (1) by scaling the gas pressure to the magnetic pressure at the field line footpoints, such that $p_0(\theta,\phi) = kB_0(\theta,\phi)$, where k is a constant. For volume elements within the corona that contain open, or closed accreting, field lines (and for field lines which have been blown open by the magnetic pressure exceeding the gas pressure) we have set the gas pressure to zero, as discussed in §3.1. The density structure of the corona is then obtained using the equation of state for an ideal gas. Finally the X-ray emission is modelled by integrating along lines of sight through an optically thin corona.

Figure 6 shows the resulting X-ray emission from the accreting field extrapolations in Figures 2 and 3 respectively. The images have been produced using 3D Monte Carlo radiative transfer codes, with 10^8 photons being released from the stellar surface and allowed to scatter through the optically thin corona. Both images only show emission from the regions of non-accreting closed field, and neglect any contribution from the accretion process.

4. Conclusions

By constructing models of CTTS which have realistic magnetic fields topologies we have demonstrated that the location of hot spots on the stellar surface is strongly dependent on the field structure. Our models suggest that hot spots should be observed at a range of latitudes, a result which broadly agrees with those of Romanova et al. (2004), who investigate the location and shape of hot spots on the surface of CTTS by considering accretion to a tilted dipole.

Magnetospheric accretion models have been relatively successful in explaining many of the observational features of CTTS, however there remain many unanswered questions regarding the nature of the accretion process and it's effects on the star. Most of the outstanding problems can be traced to questions regarding the field structure and how this affects the inner disk and the accretion process.

A new spectropolarimeter at the Canada France Hawaii telescope, ESPaDOnS: Echelle SpectroPolarimetric Device for the Observation of Stars (Petit et al. 2004; Donati et al. 2004), will in future allow the reconstruction of the magnetic field topology of CTTS from Zeeman-Doppler imaging. In 2005 we shall obtain observations of two CTTS (as well as two WTTS), which for the first time will allow magnetospheric accretion models to be produced which combine realistic physics with real magnetic fields - undoubtedly leading to some exciting new science.

Acknowledgements

The authors thank Dr A. van Ballegooijen for allowing them to use his code to calculate the potential magnetic field. SGG acknowledges the support from a PPARC studentship.

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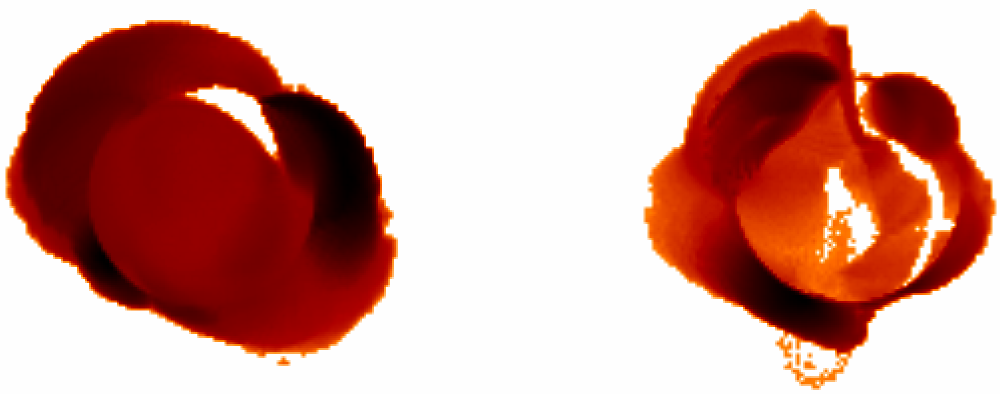

Figure 6. Left: The X-ray emission from an isothermal corona of a CTTS, at 10^6 K, assuming that it has a magnetic field topology similar to that of the K-type dwarf star LQ Hya. Right: For a CTTS with a magnetic field topology similar to that of the K-type dwarf star AB Dor.

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